INL GMD Workshop
Transformers & Model Validation

PJM Interconnection

4/8/2015

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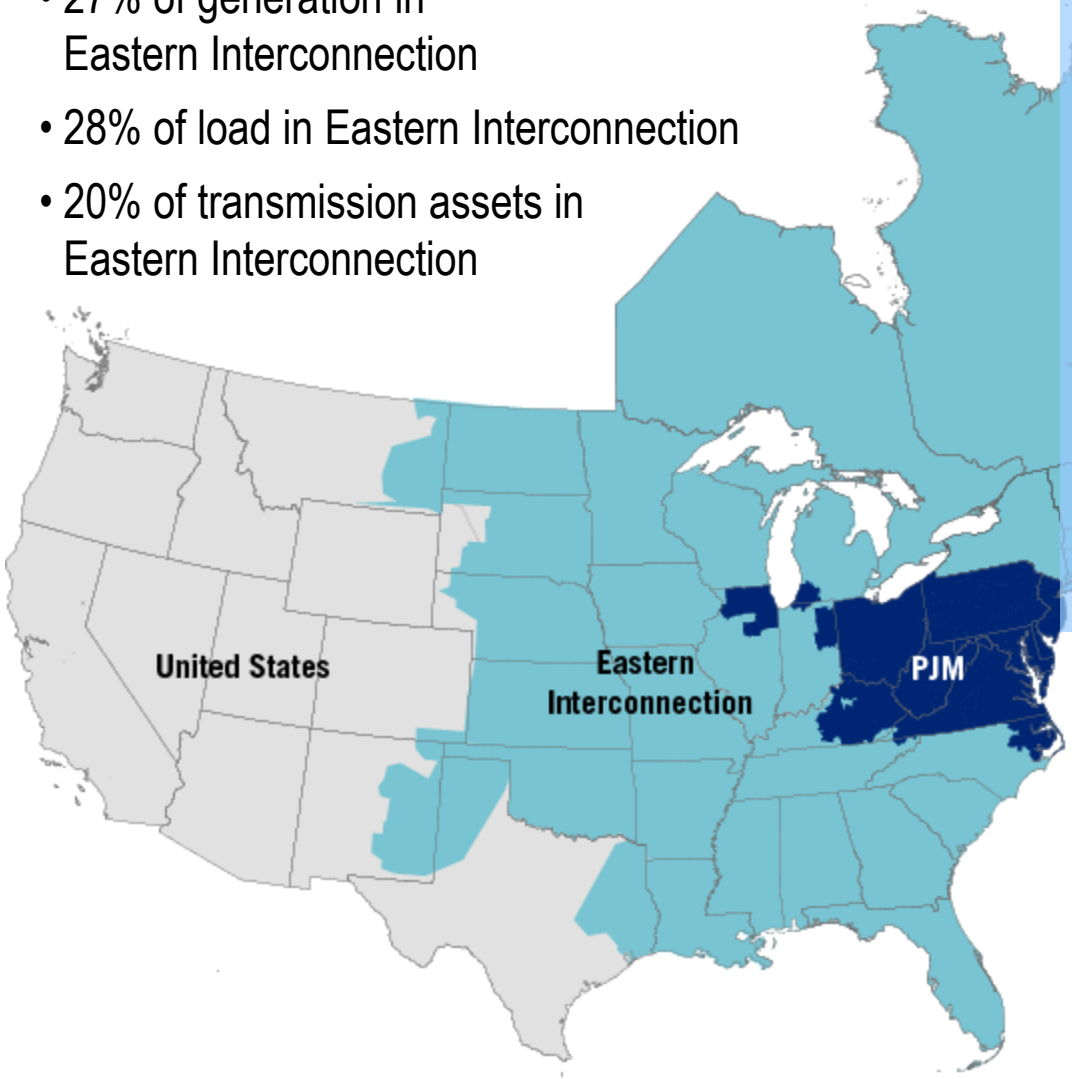
Agenda

- Introduction.
  - PJM.
  - GIC flow model – K8 event 03/17/2015.
- Transformer Models.
  - Electromagnetic model.
  - Thermal model.
- Transformer Model Validation.
  - Factory test.
- Conclusions.

PJM as Part of the Eastern Interconnection

- 27% of generation in Eastern Interconnection
- 28% of load in Eastern Interconnection
- 20% of transmission assets in Eastern Interconnection

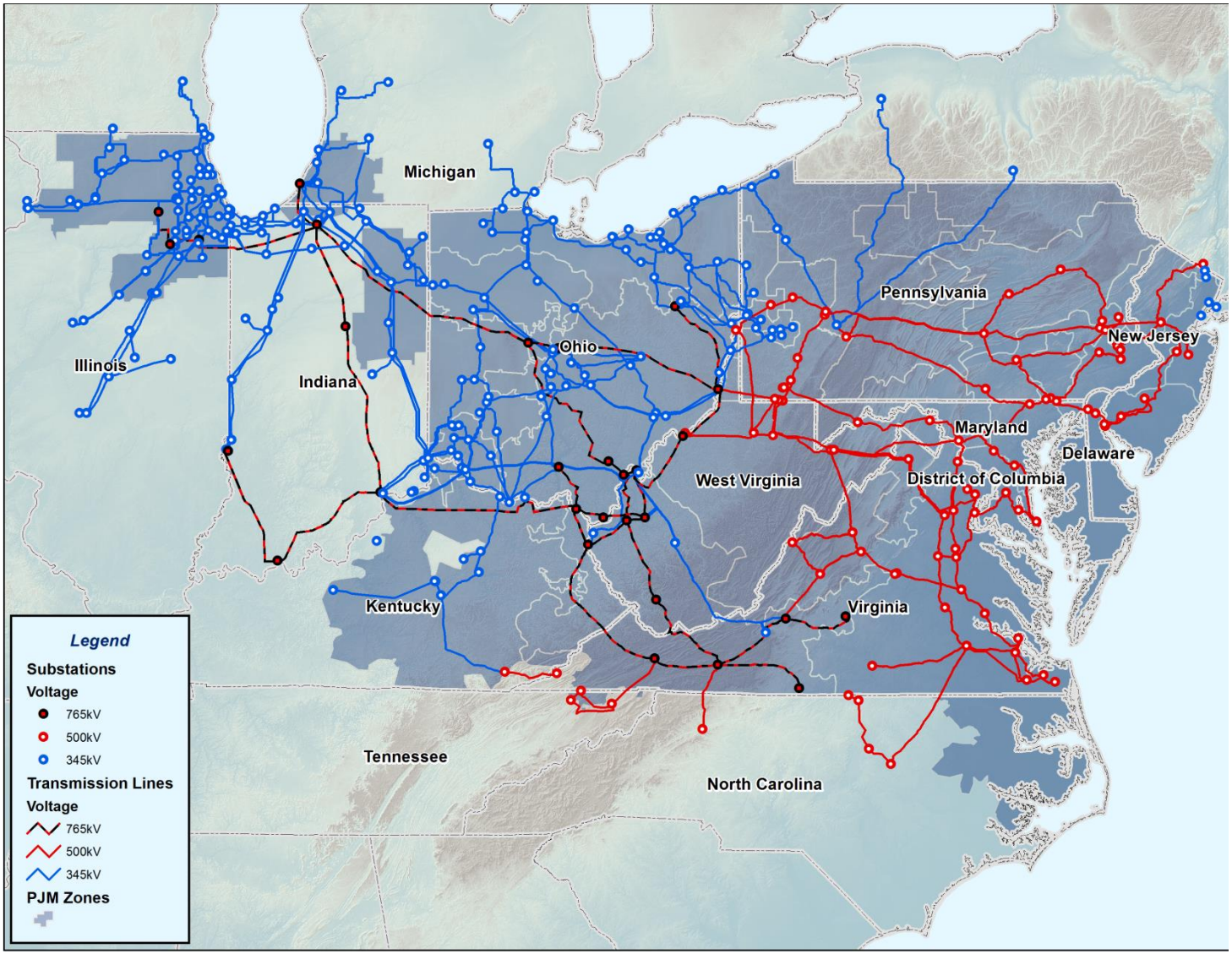


KEY STATISTICS	
PJM member companies	900+
millions of people served	61
peak load in megawatts	165,492
MWs of generating capacity	183,604
miles of transmission lines	62,556
2013 GWh of annual energy	791,089
generation sources	1,376
square miles of territory	243,417
area served	13 states + DC
externally facing tie lines	191

Eastern Interconnection

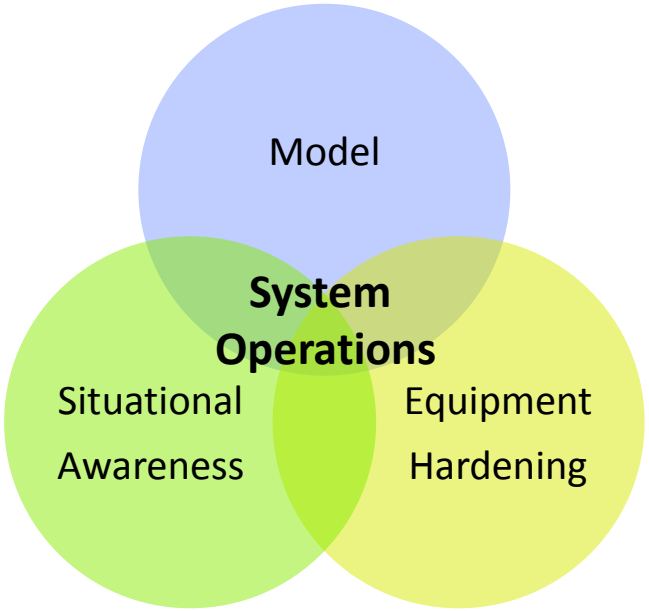
Largest Synchronized Machine

PJM Backbone Transmission



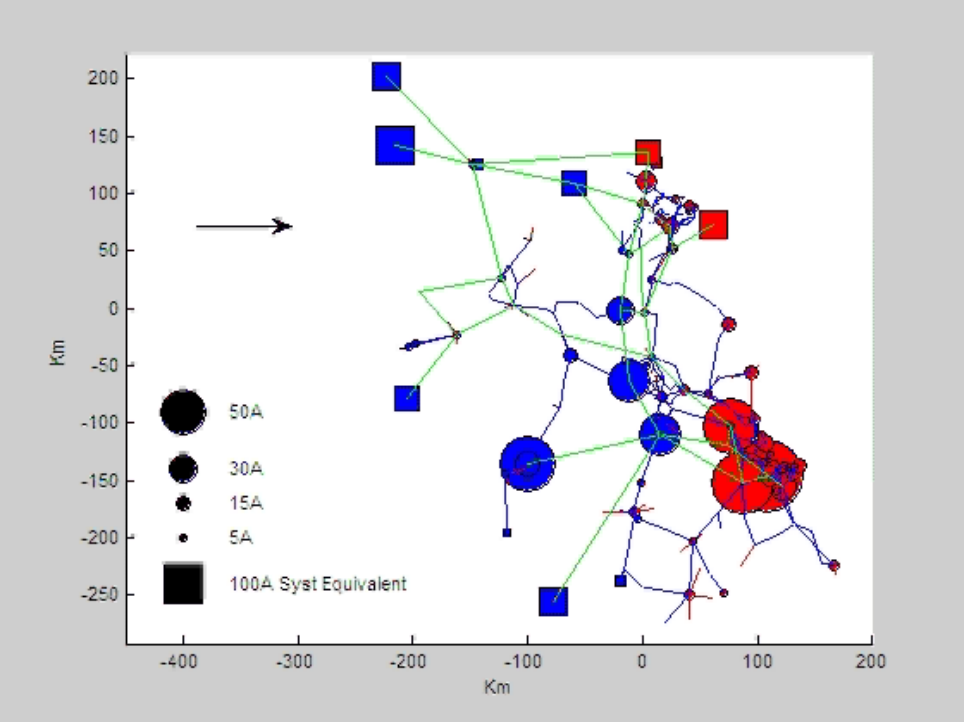
Introduction: GMD Risk Assessment and Mitigation

- Methodology:
  - 1) Situational Awareness & Operating Procedures.
  - 2) Modeling.
  - 3) Equipment hardening.



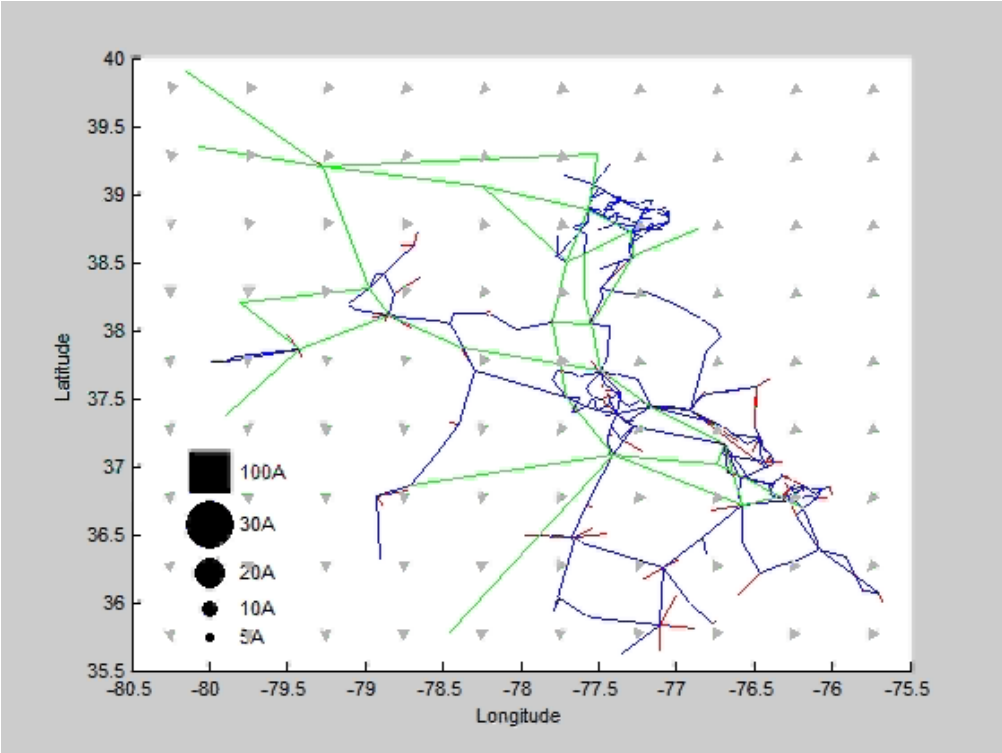
Critical Locations

- |E|=2 V/km.
- Model:
  - 497 buses.
  - 511 transmission lines.
  - 230 transformers.
- GIC is a function of:
  - Topology.
  - Transformer type.
  - Grounding resistance.
  - Line/transformer resistance.



GIC Flow: Uniform Geoelectric Field

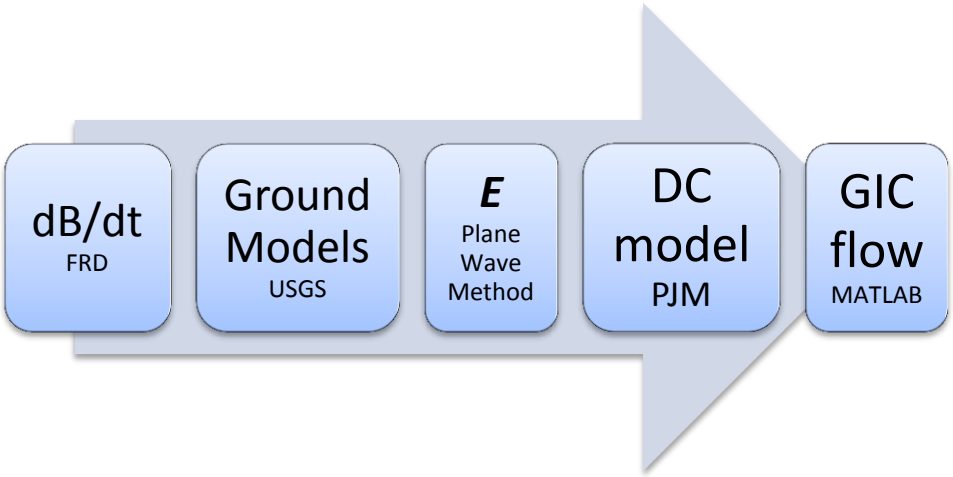
- 2003 Halloween storm.
- Unique ground conductivity.
  - Future: multiple ground conductivity.
- Uniform vs Non-Uniform:
  - Critical Locations.
  - Scales.



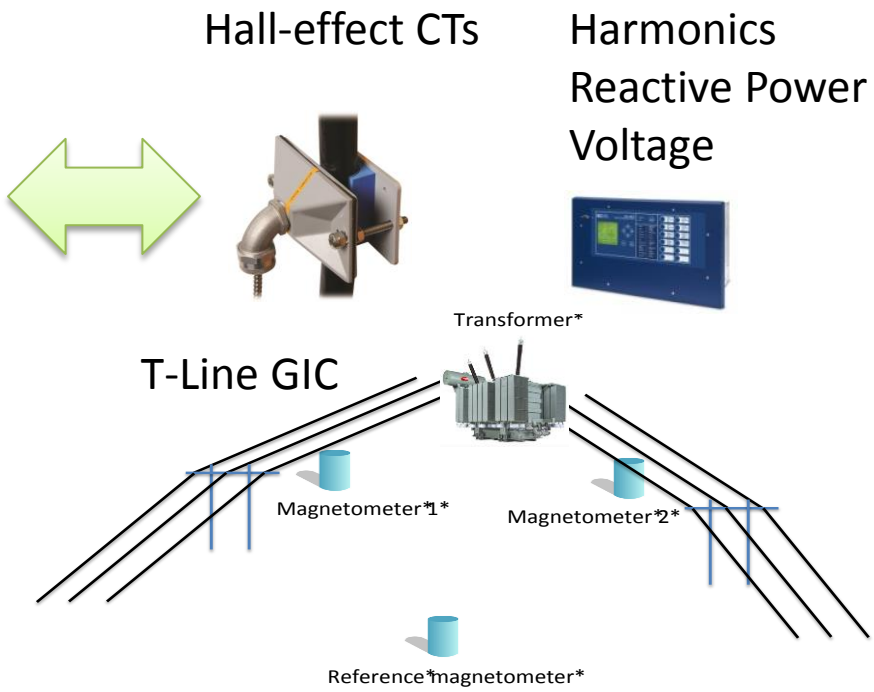
Model Validation: K8 event 03/17/2015

- GIC model validation.

Simulation



Field Measurements



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- **Transformer Models.**
  - Electromagnetic model.
  - Thermal model.
- Transformer Model Validation.
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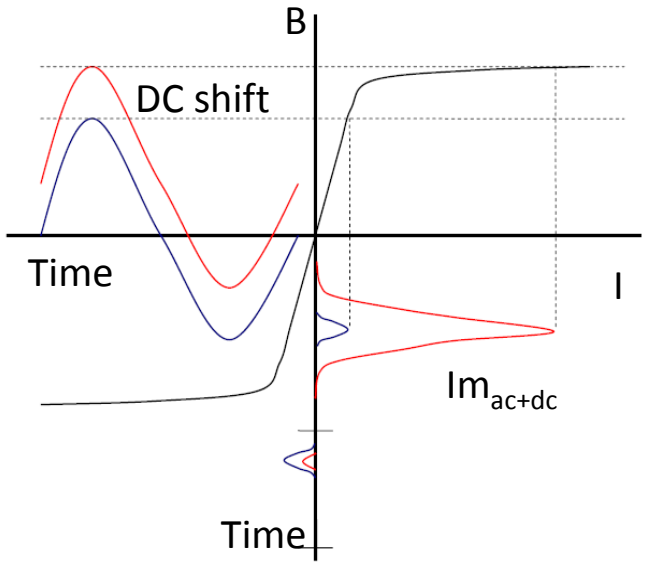
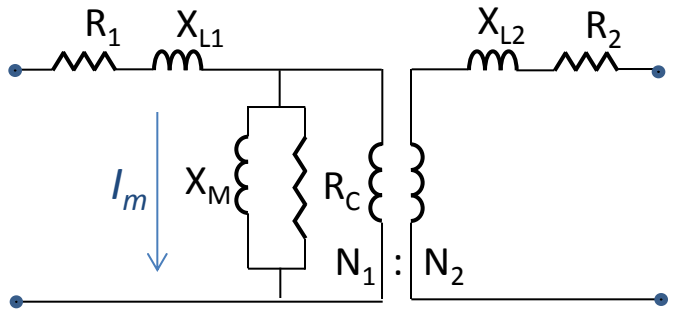
Transformer Model

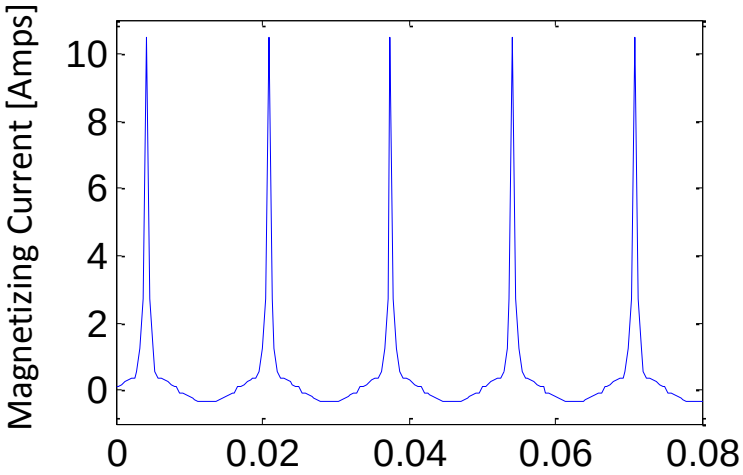
- Thermal model.
  - Transformer vulnerability → hot-spots.
- Electromagnetic model.
  - GIC vs. Q → Load flow.
  - GIC vs. Harmonics → P&C.

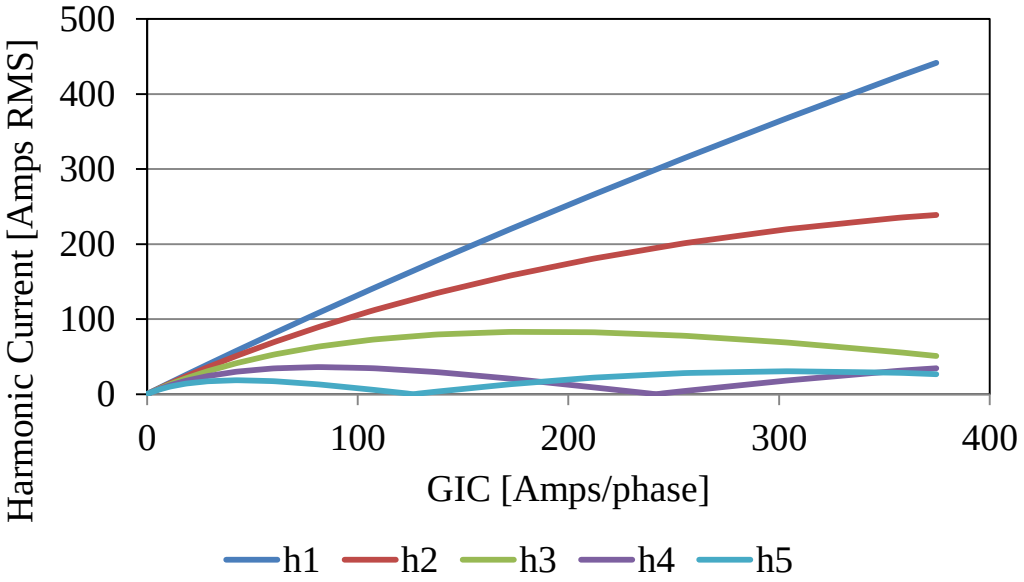


Electromagnetic Model: *H=f(GIC)*

- I_{MAG} is non-linear function of:
  - GIC.
  - Transformer core (shell/core, 1-phase/3-phase).
  - Design: air-core reactance, knee, etc.







Harmonic Load Flow

- GIC: few critical locations in the system.
- Harmonics: propagate throughout the system.

IEEE 519

Voltage	THD
< 69 kV	< 5%
< 161 kV	< 2.5%
> 161 kV	< 1.5%

Generators: Negative Sequence Heating

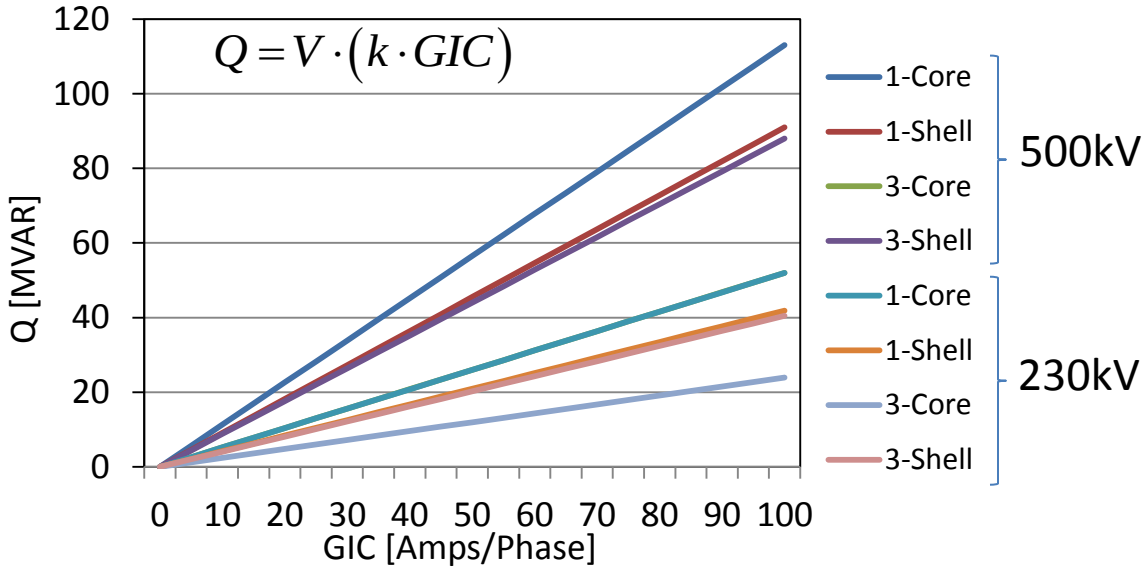
- Limit $\longrightarrow I_2 \cdot t$
  - System harmonics.
  - Natural unbalance.
  - Time: 25 minutes.

IEEE C50.13

Type of generator rotor cooling	Permissible I_2 (%)
Indirectly cooled	10
Directly cooled	—
to 350 MVA	8
351 MVA to 1250 MVA	8–(MVA–350)/300
1251 MVA to 1600 MVA	5
Above 1600 MVA	By agreement

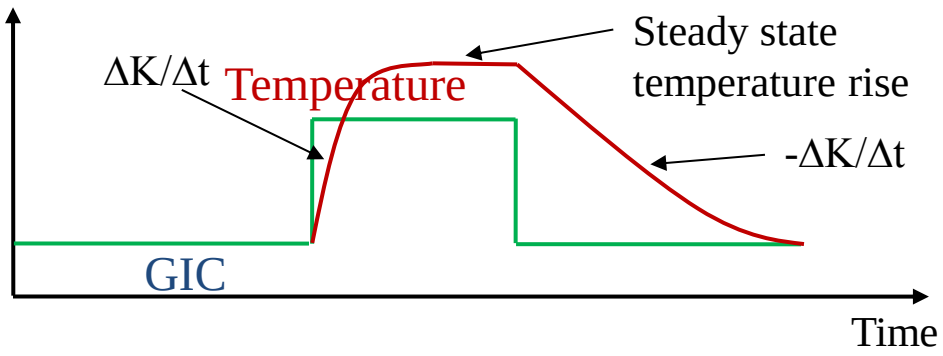
Electromagnetic Model: *Q=f(GIC)*

- Linear relationship between GIC and MVARs.
  - Incorporate to planning study.
  - Monitoring tool: PMUs.



Transformer Thermal Model

- Methodology:
  - Structural parts.
  - Windings and core.
  - Loading conditions.
  - Step up, step down.



Magnetic Branch Equivalent **3D FEM**

Structural Hot-Spot

- Stray flux ⟶ Eddy currents.
  - Yoke/winding clamps, tie plates, tank wall, shields, etc.
- Potential issues: gassing, insulation degradation, SPR?, etc.
- Technical specification: non-magnetic materials.
  - Decrease by a factor of ~10 the temperature rise.

Winding Hot-Spot

- Winding hot-spot:
  - Ohmic losses I^2R.
  - Eddy losses due to stray flux (axial, radial).
  - Circulating currents.
- Function of:
  - Ambient temperature.
  - Loading condition.
  - GIC.

Example of Calculated Temperature Rise

- Rate-of-rise and final temperature are quite different for different active and structural parts

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Test Setup

- **Objective**: validate the model (not a type test)
- Back-to-Back connection.
- Monitor:
  - Thermocouples
    - Hot-spots and cold-spots.
    - Redundant.
  - Voltages and currents.
  - Harmonics.
  - Noise and Vibration.
  - Oil sample (before and after every test).
  - Thermal imaging camera.

Back-to-Back Connection: SMIT

Back-to-Back Connection: Mitsubishi

Thermocouples

- Thermocouple placement:
  - Hot-spot locations.
  - Cold-spot locations.
  - Redundant.

Noise and Vibration

- Noise: 20 dB jump.
    - It is pretty loud.
- Vibration:
  - Function of GIC; not a big concern.

Voltages and Currents

Temperature Rise: SMIT

Conclusion

- Transformer Models:
  - Electromagnetic: MVARs, Harmonics.
  - Thermal: hot-spots.
- Thermal model key concepts:
  - Critical locations.
  - Hot-spots function GIC amplitude and spectral signature.
- Transformer model validation:
  - Factory: limited by test facility.
  - GMD events:
    - GIC (neutral & T-line).
    - Voltage & Currents.
    - Harmonics.
    - Reactive Power.
    - Thermocouples.
    - DGA.